GENERATION MECHANISM OF ULF MODULATED ION ACOUSTIC WAVES

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Abstract: Generation mechanism of ELF emissions through plasma maser effect (induced bremsstrahlung instability) in the presence of a coherent ULF wave is proposed. The results are consistent with the observation.

1. Introduction

A new type of magnetospheric electrostatic ELF wave is reported (WEHRLIN, 1981). These waves have a wide spectrum, extending between the lower hybrid frequency (ω_{lh}) and the ion plasma frequency (ω_{pi}). The corresponding electromagnetic ion cyclotron waves are detected simultaneously in all cases but one. At least two factors seem to control the existence of these events: the amplitude of electromagnetic ion cyclotron wave (E_{lz}) and the plasma density (N). According to the observation, there exists first an electromagnetic ion cyclotron wave which modulates the amplification condition of electrostatic ion acoustic waves.

The purpose of this paper is to study the growth of electrostatic ion acoustic waves in the presence of a coherent electromagnetic ion cyclotron wave. The energy up-conversion from a coherent electromagnetic ion cyclotron wave to high frequency ion acoustic waves occurs without primary electron beam.

2. Theory

According to the recent weak turbulence theory (NAMBU, 1982), we have two kinds of free electron maser effect in plasma turbulence. The first one is the inverse nonlinear Landau interaction (LIN *et al.*, 1973) which requires the electron population inversion. The second one is the induced bremsstrahlung instability found by us which occurs due to the presence of resonant electrons in plasma turbulence. The second type of maser effect markedly differs from the first type in that the new effect does not require the electron population inversion (NAMBU, 1981). The new mode coupling is applied to aurora kilometric radiation (BUJARBARUA and NAMBU, 1983) and type III radio emission (NAMBU and SHUKLA, 1983).

We consider a homogeneous magnetized plasma in the presence of an enhanced coherent electromagnetic ion cyclotron wave (PC 1) which propagates obliquely to

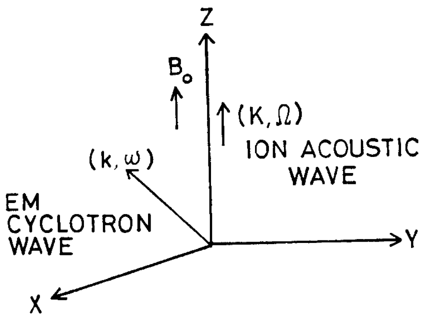

Fig. 1. *Geometry of model; **K** is the propagation vector of the electrostatic ion acoustic wave, and **k** is the propagation vector for the electromagnetic ion cyclotron wave, here $\boldsymbol{K}=(0, 0, K)$ and $\boldsymbol{k}=(k_\perp, 0, k_\parallel)$.*

the magnetic field. Next, we perturb the steady state by introducing a high frequency electrostatic ion acoustic test field (ELF wave) which propagates along the magnetic field (see Fig. 1).

According to the linear response theory of a turbulent plasma, the effective nonlinear dielectric constant of ion acoustic waves [$\varepsilon(K, \Omega)$] in the presence of a coherent ion cyclotron wave is reduced to

$$\varepsilon(K, \Omega)=\varepsilon_0(K, \Omega)+\varepsilon_N(K, \Omega)\ , \tag{1}$$

where $\varepsilon_0(K, \Omega)$ is the linear dielectric constant of ion wave

$$\varepsilon_0(K, \Omega)=1-\frac{\omega_{pe}^2}{K}\int\frac{\dfrac{\partial f_{oe}}{\partial v_\parallel}}{Kv_\parallel-\Omega}\mathrm{d}v_\parallel-\frac{\omega_{pi}^2}{K}\int\frac{\dfrac{\partial f_{oi}}{\partial v_\parallel}}{Kv_\parallel-\Omega}\mathrm{d}v_\parallel\ , \tag{2}$$

$\varepsilon_N(K, \Omega)$ is the most dominant mode coupling term (polarization)

$$\begin{aligned}\varepsilon_N(K, \Omega)=&\frac{\omega_{pe}^2}{iK}\int\frac{1}{Kv_\parallel-\Omega}\frac{\partial}{\partial v_\parallel}\left(\frac{e}{m}\right)\frac{E_{lz}(-k, -\omega)}{\omega-k_\parallel v_\parallel-io}\frac{\partial}{\partial v_\parallel}f_{oe}\,\mathrm{d}v_\parallel\\&\times\frac{\omega_{pe}^2}{R}\int\left[\frac{J_1^2}{\Omega-\Omega_e-(K+k_\parallel)v_\parallel}+\frac{J_1^2}{\Omega+\Omega_e-(K+k_\parallel)v_\parallel}\right]\\&\times\frac{\partial}{\partial v_\parallel}\left(-\frac{e}{m}\right)\frac{E_{lz}(k, \omega)}{i(\omega-k_\parallel v_\parallel+io)}\frac{\partial}{\partial v_\parallel}f_{oe}\,\mathrm{d}\boldsymbol{v}\ ,\end{aligned} \tag{3}$$

here

$$R=\frac{|K+\boldsymbol{k}|^2}{K+k_\parallel}+\sum_j\frac{4\pi e_j^2}{m_j}\int\sum_{a,b}\frac{J_aJ_b\exp[i(a-b)\phi]}{\Omega+\omega-b\Omega_j-(K+k_\parallel)v_\parallel}\frac{\partial}{\partial v_\parallel}f_{oj}\,\mathrm{d}\boldsymbol{v}\ . \tag{4}$$

The io in the denominator in eq. (3) represents the small imaginary term which shows the contour in evaluating the denominator. ω_{pe} and ω_{pi} are the electron and ion plasma frequency, respectively. The symbol $\|$ means parallel to the magnetic field. In eq. (4), only $n=0$ in $\sum_n (J_n^2 \cdots)$ is kept because $\Omega\ll\Omega_e$, here Ω_e is the electron cyclotron frequency. E_{lz} is the field aligned electric field of PC 1, f_{oe} is the Maxwell distribution function for electrons. (Ω, K) and (ω, k) are the frequency, wavenumber of the ELF and a coherent PC 1 wave, respectively.

The imaginary part of eq. (2) gives the Landau damping rate (γ_0) of the ion acoustic wave

$$\frac{\gamma_0}{\Omega}=-\left(\frac{\pi}{8}\right)^{1/2}\left(\frac{T_e}{T_i}\right)^{3/2}\exp\left[-\frac{T_e}{2T_i}\right], \tag{5}$$

where T_e and T_i are the electron and ion temperature, respectively.

The condition of the induced bremsstrahlung interaction is simply $\omega=k_{\parallel}v_{\parallel}$. The nonlinear growth rate (γ_N) of the ion acoustic wave in the presence of a coherent electromagnetic ion cyclotron wave reduces (NAMBU and SHUKLA, 1983)

$$\frac{\gamma_N}{\Omega}=-\frac{I_m\varepsilon_N(K,\Omega)}{\Omega\left[\dfrac{\partial R_e\varepsilon_0}{\partial\Omega}\right]_{\Omega=KC_S}}=\frac{\pi}{4}\left(\frac{\omega_{pe}}{\Omega_e}\right)^4\left(\frac{m}{M}\right)^{1/2}\left(\frac{v_e}{v_A}\right)^4\left(\frac{k_\perp}{k_\parallel}\right)^2$$
$$\times\frac{K}{|k_\parallel|}\left(\frac{K}{k_e}\right)^2\frac{|E_{lz}(k,\omega)|^2}{4\pi NT}\exp\left[-\left(\frac{v_A}{v_e}\right)^2\right]. \tag{6}$$

It is instructive to compare eq. (5) with eq. (6). It emerges that one can have the turbulent plasma with enhanced both the ion sound waves and a PC 1 wave under the condition

$$\gamma_N+\gamma_0>0. \tag{7}$$

Accordingly, the critical threshold amplitude of a PC 1 wave for the onset of the induced bremsstrahlung instability is

$$\frac{|E_{lz}|^2}{4\pi NT}>\left(\frac{2}{\pi}\right)^{1/2}\left(\frac{T_e}{T_i}\right)^{3/2}\exp\left[-\frac{T_e}{2T_i}\right]\left(\frac{\Omega_e}{\omega_{pe}}\right)^4\left(\frac{M}{m}\right)^{1/2}\left(\frac{v_A}{v_e}\right)^4\left(\frac{k_\parallel}{k_\perp}\right)^2$$
$$\times\frac{|k_\parallel|}{K}\left(\frac{k_e}{K}\right)^2\exp\left[\left(\frac{v_A}{v_e}\right)^2\right]. \tag{8}$$

3. Discussions

First, we show that the condition of instability eq. (8) is satisfied under the following plasma parameters: $\omega/2\pi=1$ Hz, $\Omega/2\pi=300$ Hz, $k_\parallel/k=5\times10^{-2}$, $v_e/v_A=1$,

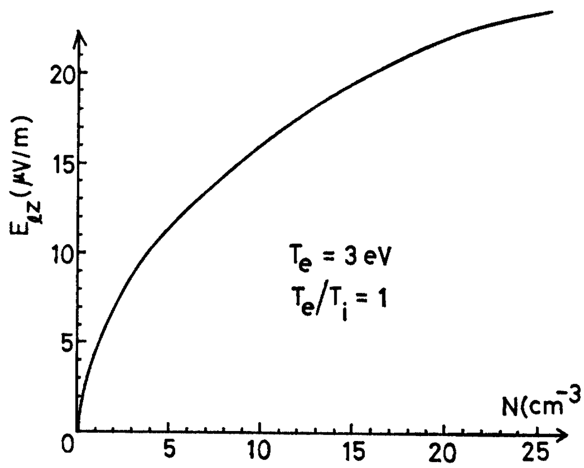

Fig. 2. The critical EM ion cyclotron wave amplitude $E_{lz}(\mu V/m)$ versus electron number density N (cm^{-3}) for T_e=3 eV and T_e/T_i=1. The electrostatic ion acoustic wave becomes unstable above the solid line.

$T_e/T_i=1$, $K/k_e=10^{-2}$ and $K/k_\parallel=10^4$. Here, v_e and v_A are the electron thermal velocity and Alfvén velocity, respectively. Then, the critical amplitude of a PC 1 wave $(|E_{lz}|^2/4\pi NT)_C$ reduces to

$$(|E_{lz}|^2/4\pi NT)_C=3\times10^{-10}\ . \tag{9}$$

Figure 2 is a plot of the critical amplitude (E_{lz}, in unit of μV/m) *vs.* electron number density (N, in unit of cm^{-3}). Note that the induced bremsstrahlung instability of ELF emission occurs above the solid line. Equation (9) predicts that the strong amplitude of E_{lz} and small value of N favor the instability which is consistent with the observation (WEHRLIN, 1981). Furthermore, the typical values ($E_{lz}=10$ μV/m, $N=4$ cm^{-3}, $T_e=3$ eV) satisfy the instability condition (eq. (8)).

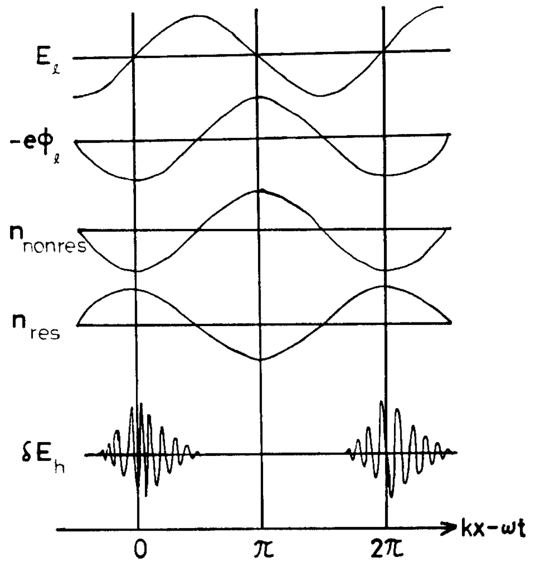

Fig. 3. Phase relation of density for electrons in a low frequency pump field. E_l and $-e\phi_l$ are the electric field and the potential of the low frequency wave. $n_{\rm nonres}$ and $n_{\rm res}$ show the number density for the nonresonant electrons and resonant electrons. $\delta E_{\rm h}$ is the high frequency radiation field. The high frequency radiation occurs at the particular phase due to the turbulent bremsstrahlung instability.

Next, the new maser effect predicts a particular phase relation between a pump field (PC 1) and the high frequency emission (ELF). The first two curves in Fig. 3 show the electric field E_l and the potential $-e\phi_l$ seen by the electrons. The third and fourth curves are plots of the nonresonant and the resonant electron number density perturbation due to a coherent low frequency pump wave (E_l). We see easily that resonant electrons are rich in density for the potential energy minimum. The resonant electrons are necessary ($\omega=k_\parallel v_\parallel$) to transfer energy from a pump field to the radiation field. Accordingly, the expected high frequency bursts due to the turbulent bremsstrahlung instability have a close correlation in phase with that of resonant electrons number density. The bottom curve in Fig. 3 represents the high frequency radiation field *vs.* phase $kx-\omega t$. We must note that Fig. 2 reported by WEHRLIN (1981) also shows such a phase relation between a low frequency ULF wave and high frequency ELF emissions.

Third, in contrast to the parametric instability, the new maser effect predicts a wide spectrum of the high frequency radiation. Because, the new instability does not require the matching conditions between frequencies and wavenumbers. We must note that the observation also reported such a wide spectrum of ELF emissions extending between the lower hybrid frequency and the ion plasma frequency. The upper cutoff frequency of ion wave is ω_{pi} which is reported by the observation. The growth rate of the ion wave is small for long wavelength (low frequency) because $\gamma_N/\Omega \propto K^3$ (eq. (6)). Accordingly, there is a lower cutoff frequency of the ELF wave which corresponds to $\Omega \sim \omega_{lh}$.

Fourth, the induced bremsstrahlung instability does not require population inversion of electrons. Indeed, the growth rate eq. (6) is obtained for the Maxwell distribution function. If we assume the electron beam along the magnetic field, then the growth rate is much enhanced (NAMBU, 1981). Furthermore, this does not contradict the observation (NORRIS *et al.*, 1983) that thermal (1 eV) electrons are accelerated along field lines (up to tens of eV) when intense PC 1 waves are simultaneously present. Because, the Landau interaction between thermal electrons and a coherent PC 1 wave causes the acceleration of the thermal electrons through the induced bremsstrahlung instability. Accordingly, as a result of the instability, the electrons are accelerated along field lines which are observed (NORRIS *et al.*, 1983).

Thus, we can say that observations are consistent with the hypothesis that the ELF emissions are generated through the induced bremsstrahlung instability between resonant electrons and intense electromagnetic ion cyclotron waves. Table 1 summarizes the previous studies on plasma maser effect (bremsstrahlung instability) in space physics.

Table 1. Plasma maser effect in space plasma physics.

	Theory	Observation
I)	Type III radio bursts	
	NAMBU and SHUKLA (1979, 1983)	LIN *et al.* (1981)
II)	Auroral kilometric radiation	
	BUJARBARUA and NAMBU (1983, 1984)	GURNETT (1974)
III)	Chorus related bursts	
	BUJARBARUA *et al.* (1984)	REINLEITNER *et al.* (1982)
IV)	Modulation between Pc I and ELF	
	This study	WEHRLIN (1981)

Finally, the physical mechanism of the plasma maser effect is clarified based on the high frequency nonlinear forces (NAMBU, 1984). The high frequency nonlinear forces comes from the resonant electrons whose velocities are close to the phase velocity of a low frequency wave.

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